

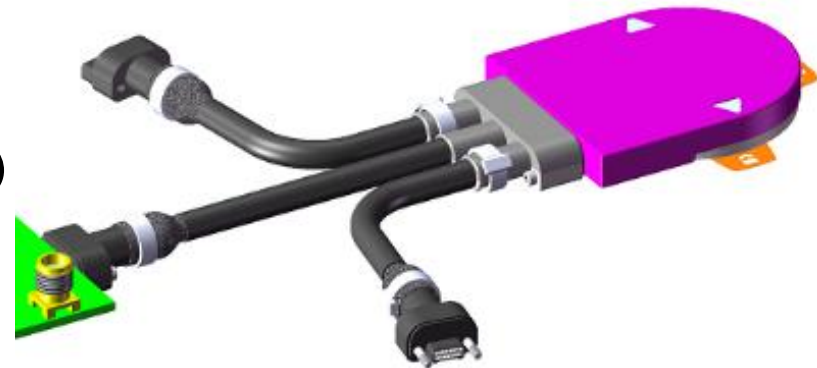
# PZT & CNT based SHM Systems for Impact Detection & Localization

Seth S. Kessler, Ph.D. | President/CEO  
Metis Design Corporation | 15 July 2014

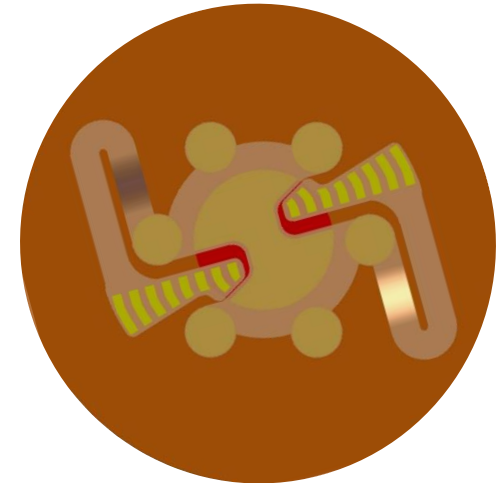


# MD7-Pro Digital SHM System

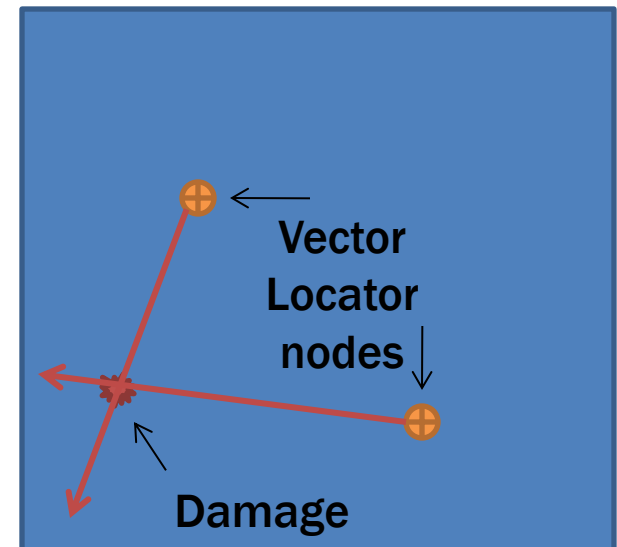
- **Metis Design developed & validated system through SBIR funding**
  - AF03-T017 – Intelligent SHM Infrastructure (hardware)
  - AF06-097 – Adaptive Damage Detection (software)
  - USS Independence (N10-T042)
  - Triton UAS (N12-125)
  - Blackhawk (N12-T007, COST-A & others)
- **System focus on low mass, low power, expendability, retro-fit**
  - novel sensor/algorithm design for large-area coverage
  - distributed intelligence on a digital sensor bus
  - multifunctional capabilities at each node location



# MD7-Pro Structural Sonar

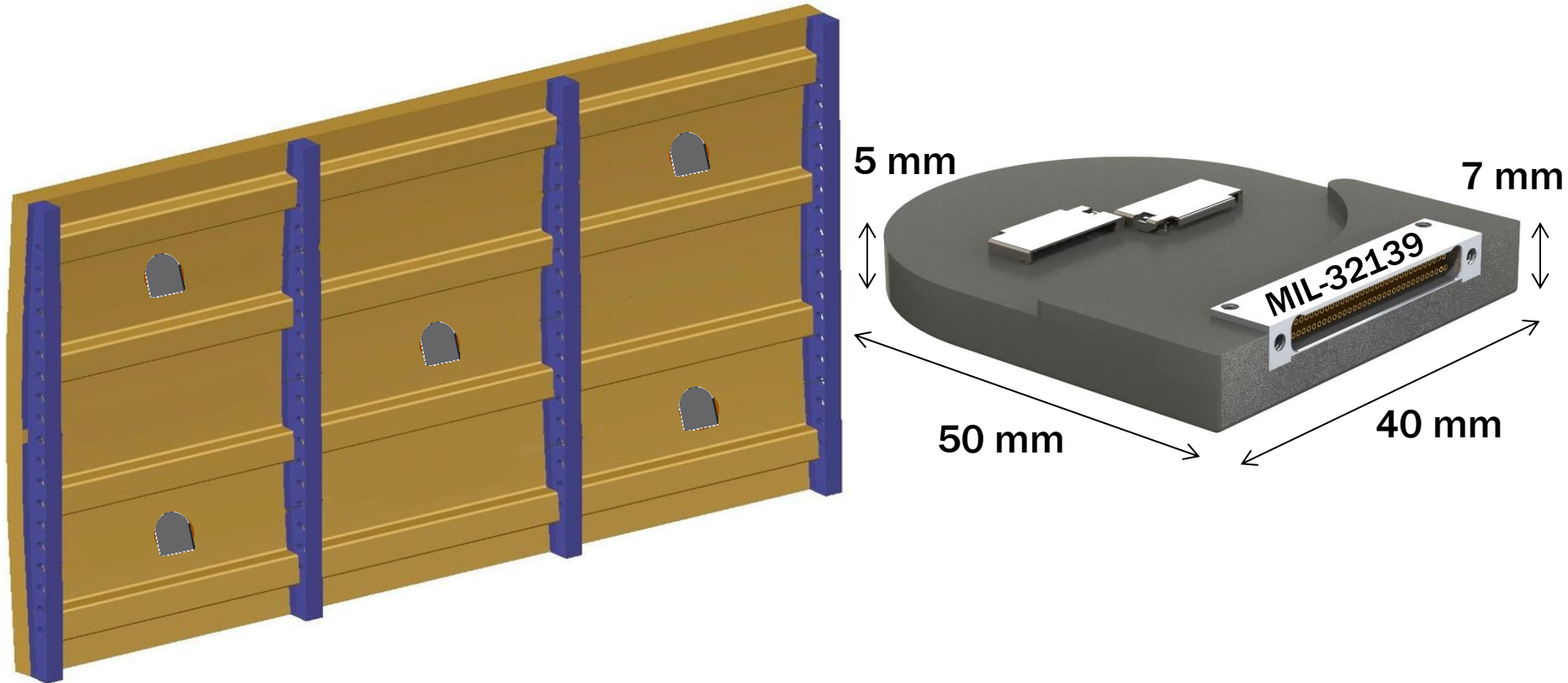


15 mm



- Analog sensor base for impact/damage detection
- Greatly reduces typically required sensor density
- 1 PZT actuator & 6 PZT sensors in small package
- Facilitates both active/passive beamforming

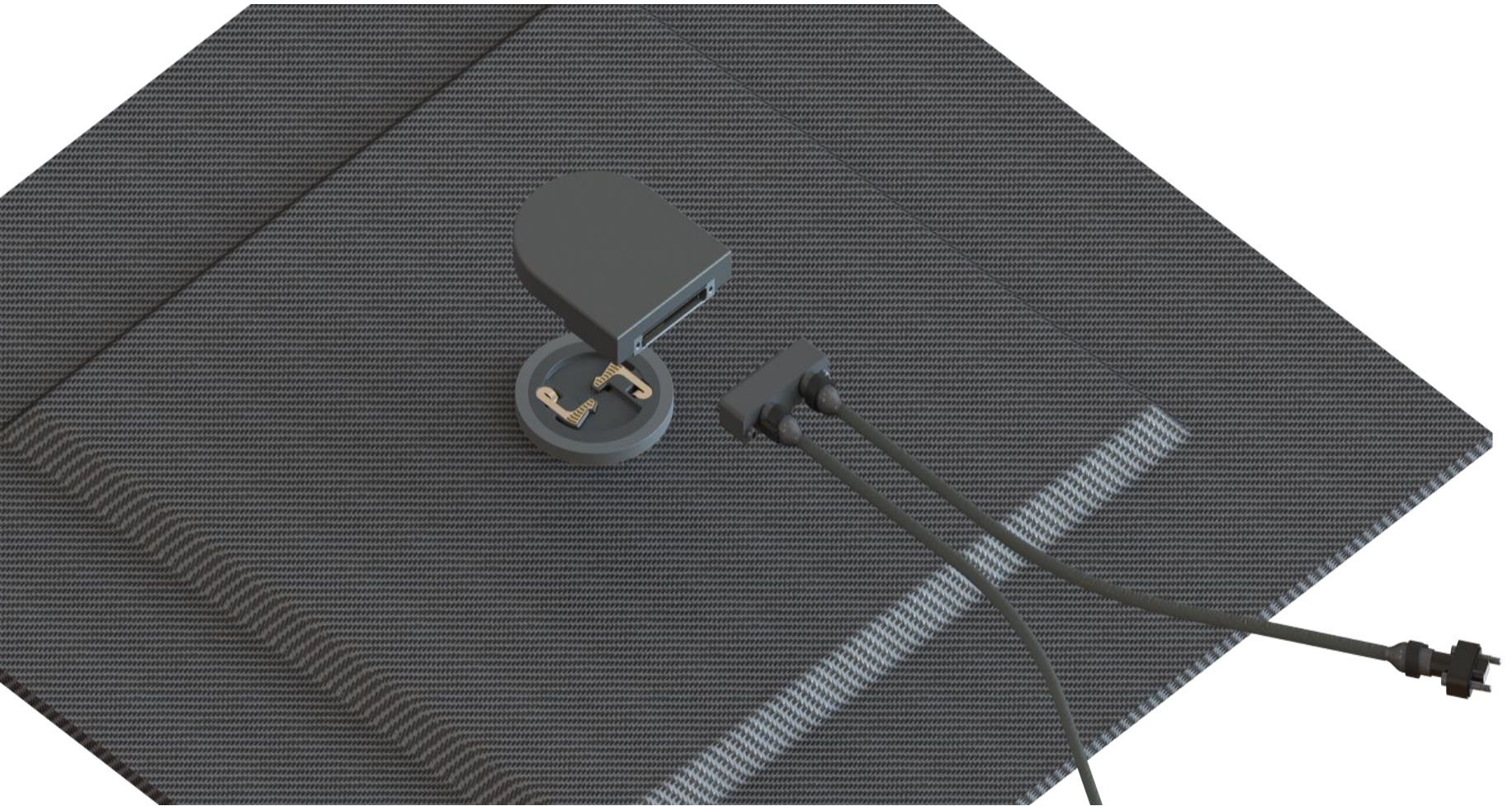
# MD7-Pro Acquisition Node



- Digital node for distributed acquisition & local computation (15 g mass)
- Greatly reduces mass of cables & centralized hardware, eliminates EMI
- Facilitates both active (guided wave) & passive (AE) detection methods
- 8 breakout analog & digital channels + built-in triaxial accelerometer & temp

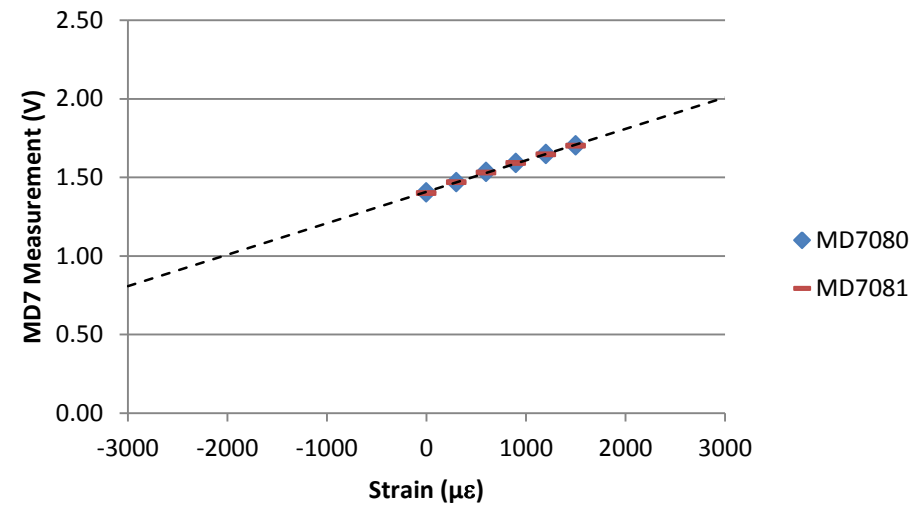


# MD7-Pro Acquisition Node + Structural Sonar

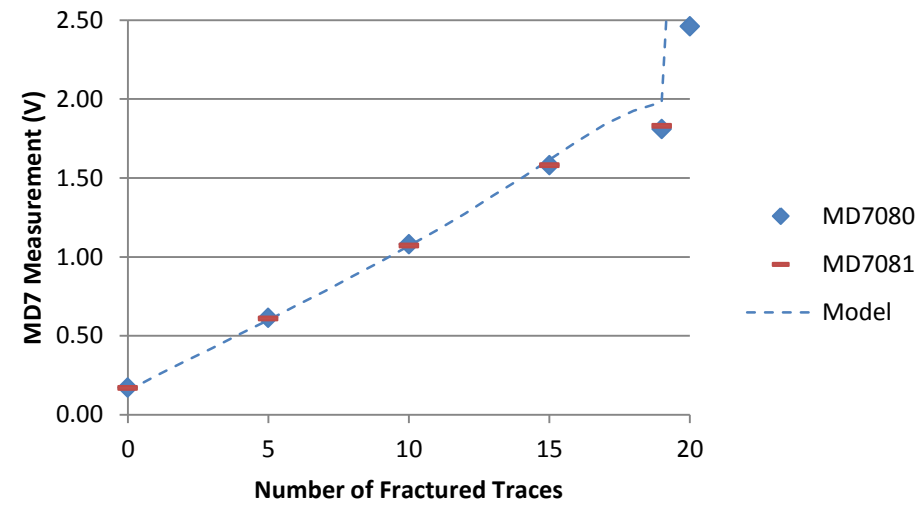


# MD7-Pro Low Speed Channel Validation

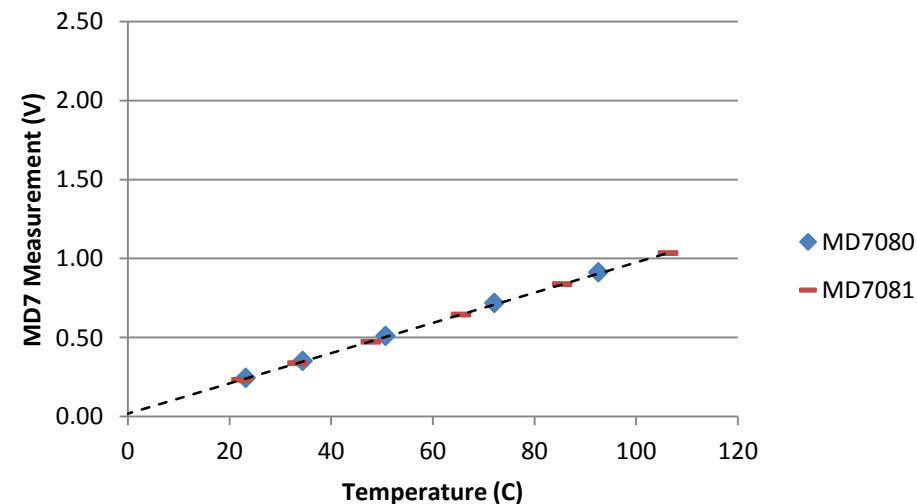
Strain Gauge Calibration & Validation



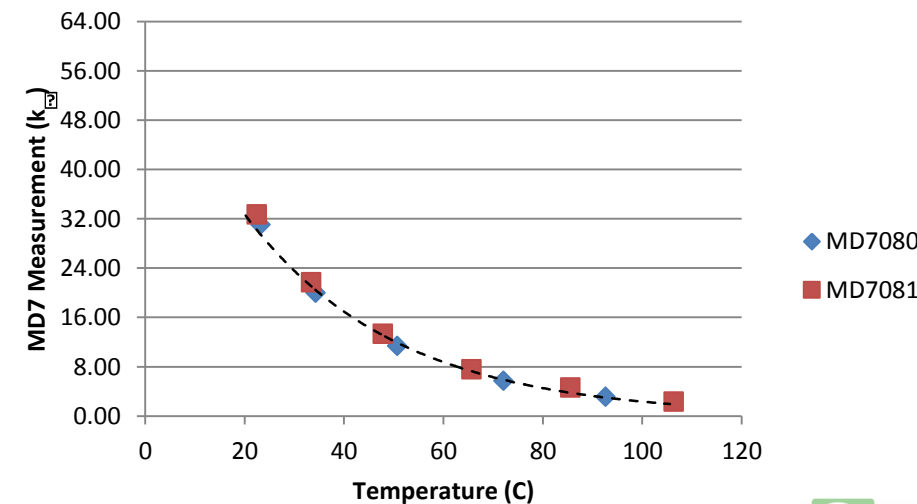
Crack Gauge Calibration & Validation



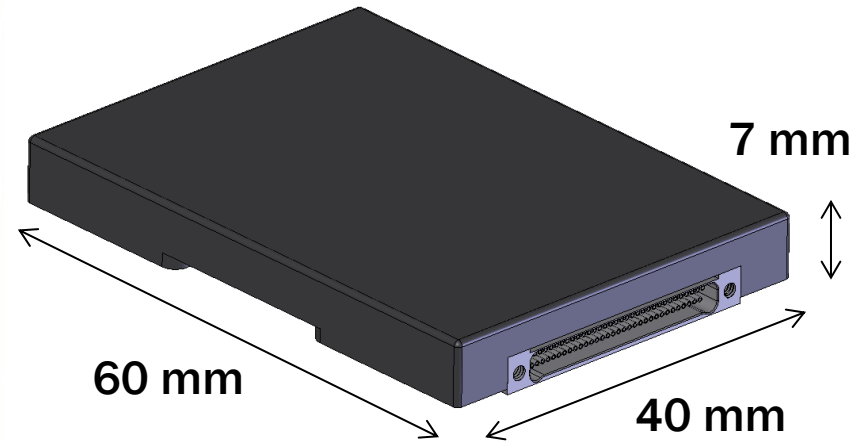
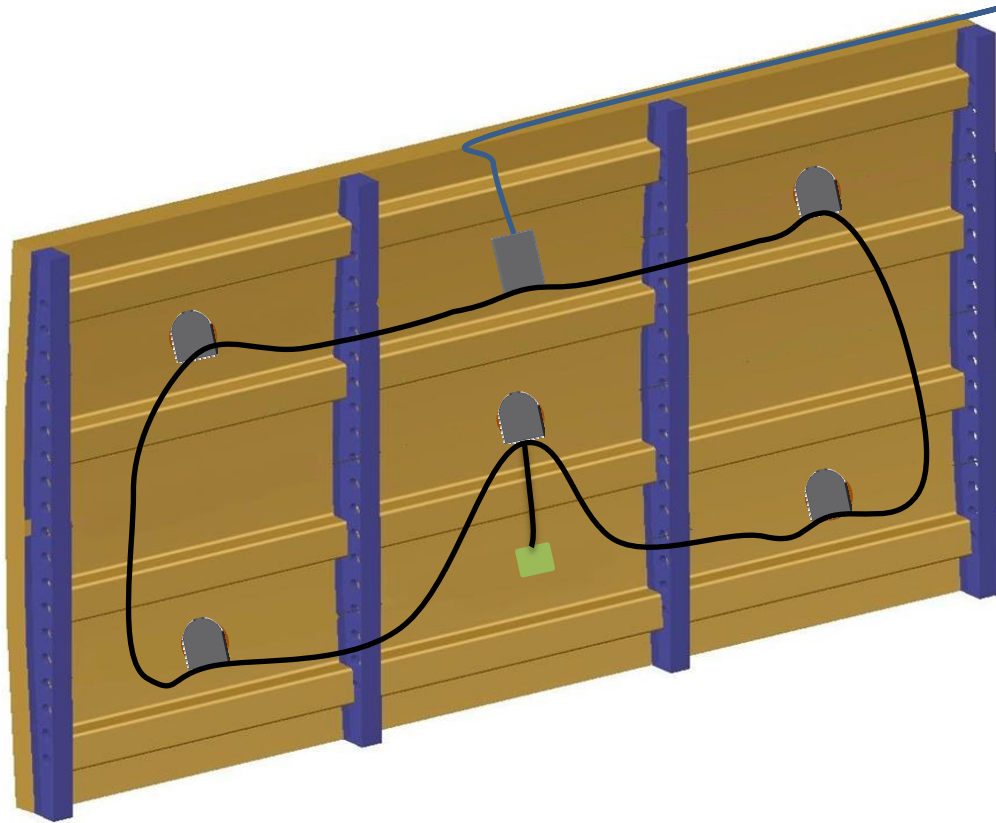
Thermocouple Calibration & Validation



Thermistor Calibration & Validation



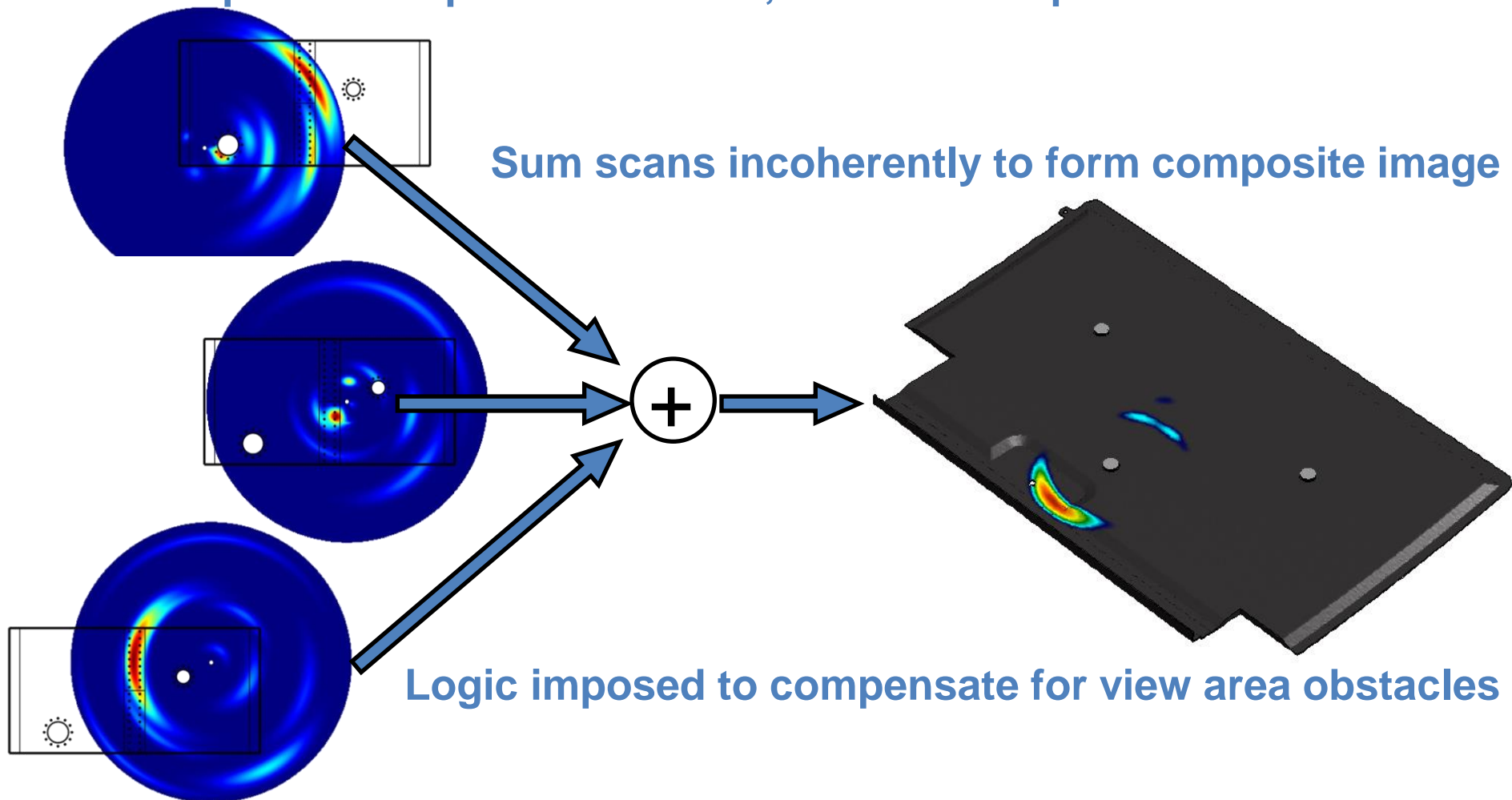
# MD7-Pro Accumulation Node



- Digital node for 64 GB data accumulation & global processing (20 g mass)
- Can support up to 100 Acquisition nodes on serial bus
- Hosts complex C++ embedded algorithms w/FPGA & 2 GB RAM
- Gigabit Ethernet + USB access to data, programmable interface

# Data Analysis & Reconstruction

Each node processes phase-coherent, location independent “sonar-scan”



color represents # of standard deviations above mean of damage-free data

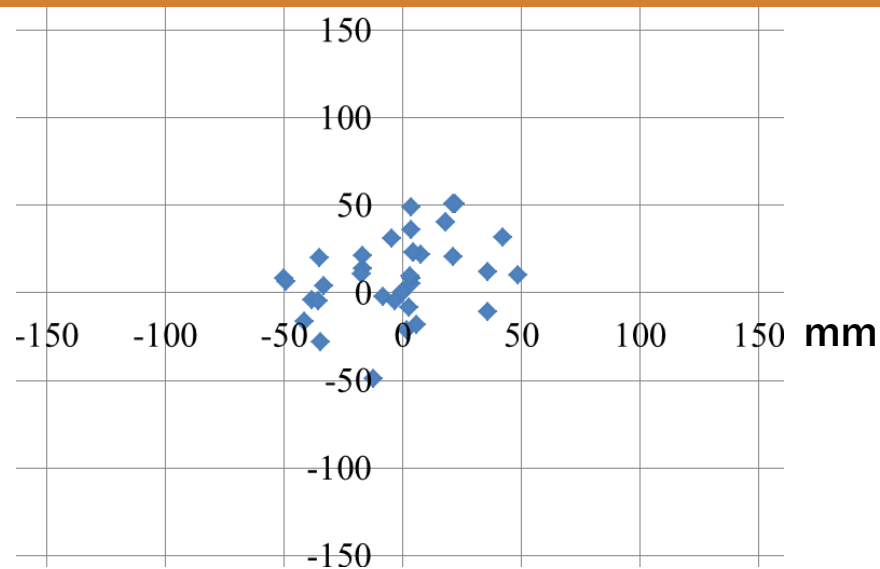


# Performance Evaluation



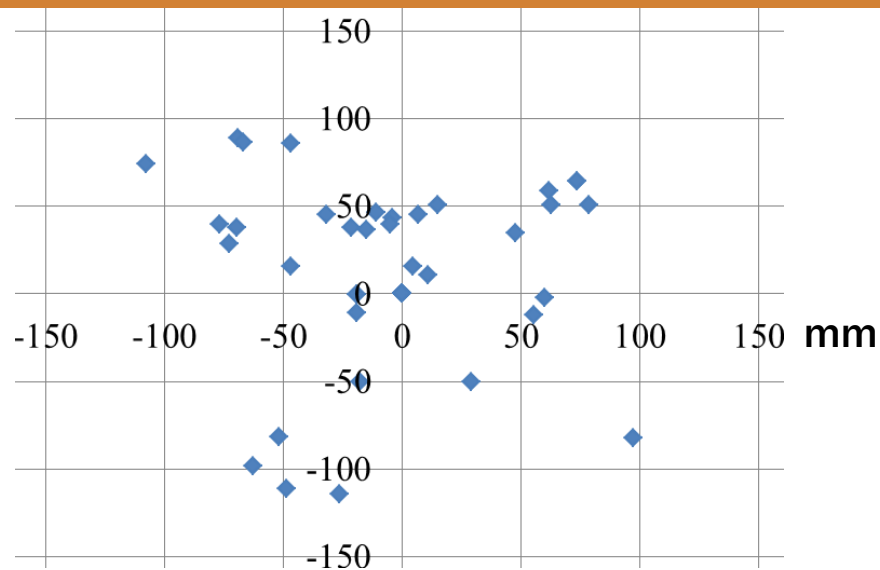
- **Single MD7 node detection on 2mm thick Al plate with 20 rivets**
  - 36 impact events of ~20 J of energy from falling 1 cm semi-spherical mass
  - half of impact on each side of rivet line
- **Hybrid passive/active detection demonstrated**
  - 36 passive/active auto-triggered measurement following impact events
  - 6 manually triggered active measurements with a fastener removed
  - 36 manually triggered active measurements without any impact or damage

# Passive Mode Impact Detection Results



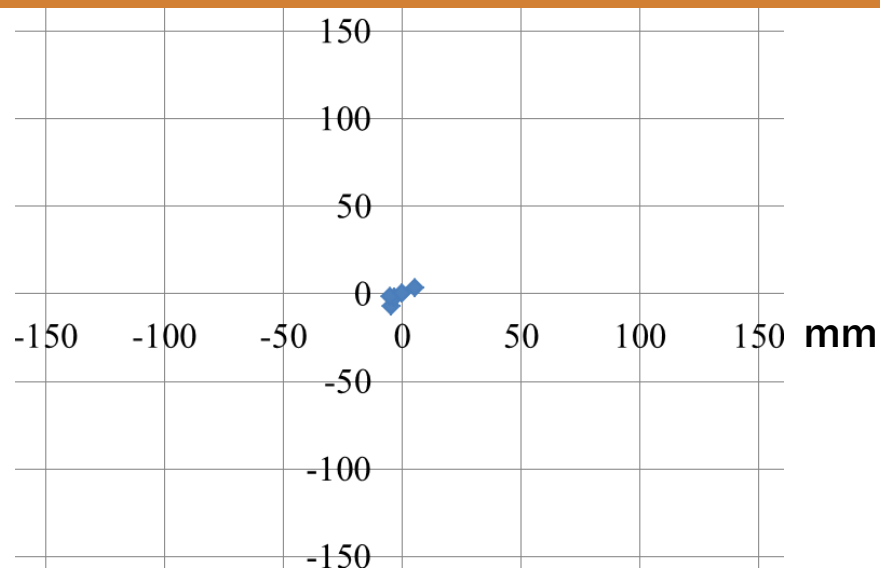
- **Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin**
  - 100% detection (36/36) following impact events
  - no false triggers recorded at pre-set threshold levels
  - mean error for AE localization ~ 25 mm
  - predictions cluster relatively closely near origin relative to size of plate
  - no trend observed for results obtained on one side of fastener line vs other

# Active Mode Impact Detection Results



- **Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin**
  - 100% detection (36/36) of ~0.5 mm deep dents following AE detection
  - no false positives indicated (0/36) following non-impact scans
  - mean error for GW localization ~ 50 mm
  - more scattered than AE, but predictions still group relatively close to origin
  - no trend observed for results obtained on one side of fastener line vs other

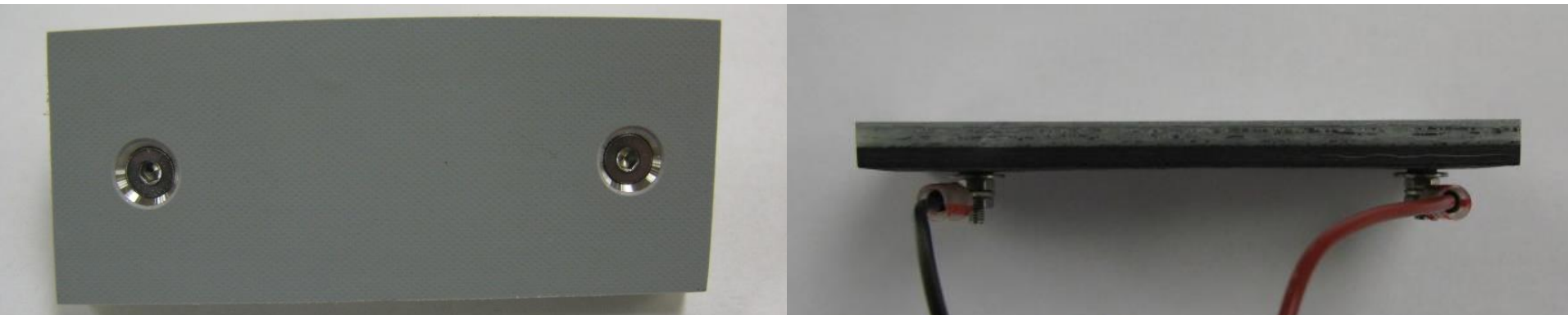
# Active Mode Fastener Detection Results



- **Results collapsed to a single scatter plot of raw localization prediction by re-centering all impacts to a common origin**
  - 100% detection (6/6) of hand-tightened fasteners
  - no false positives indicated (0/36) following non-loosened scans
  - mean error for GW localization ~ 5 mm
  - least amount of scatter due to massive local stiffness change
  - essentially translates to localization within  $\pm 1$  fastener position

# Conformal Multi-functional Assemblies

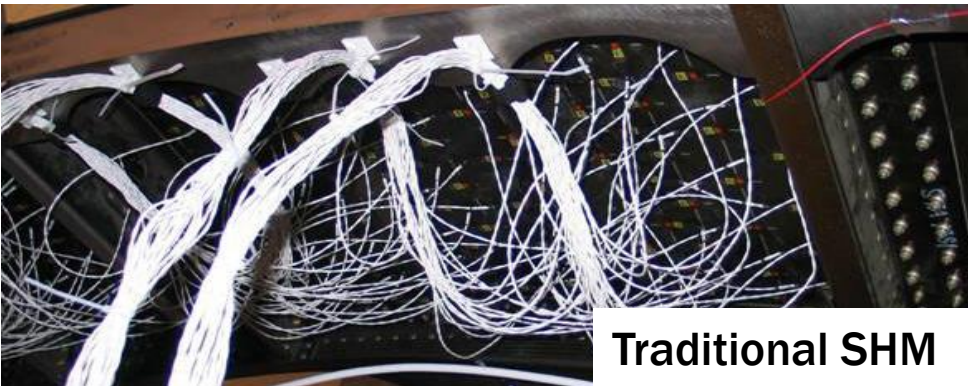
- **Conformal assemblies for composite & metallic host structures**
  - central carbon nanotube (CNT) layer is core to these properties
  - surrounded by electrically insulating layers (film adhesive and/or GFRP)
  - selective electrodes integrated to steer current flow
- **Little impact to physical structure, 100 - 200  $\mu\text{m}$  & 5 - 10  $\text{g}/\text{m}^2$** 
  - can be co-cured with composite laminate
  - can be installed over composite or metallic skin in secondary process
- **Enable multi-functional capabilities: anti-icing, health monitoring**



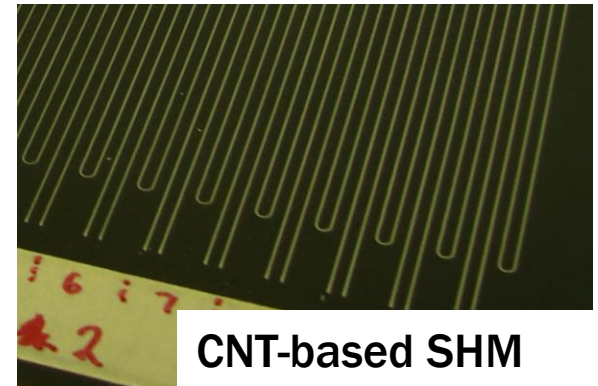


# Structural Health Monitoring (SHM)

- **SHM improves reliability, safety & readiness @ reduced costs**
  - sensors add weight, power consumption & computational bandwidth
  - cables add weight, complexity, as well as durability & EMI concerns
  - scaling SHM for large-area coverage has presented challenges
- **Advantages of proposed CNT-based SHM methodology**
  - CNT “sensors” can actually improve specific strength/stiffness of structure
  - can use thinner/lighter electrodes such as metal-mesh or direct-write
  - simple to scale over large structure, maintains good local resolution

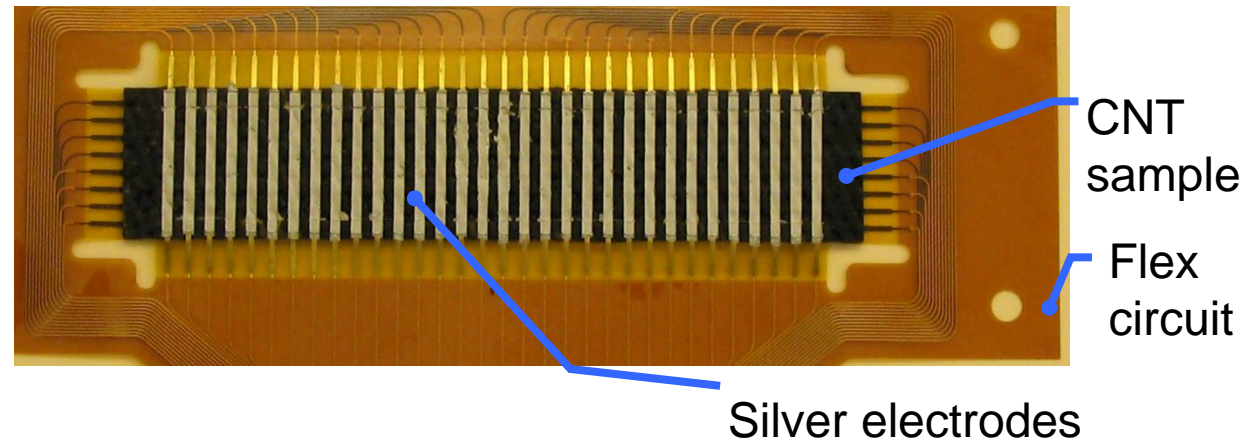
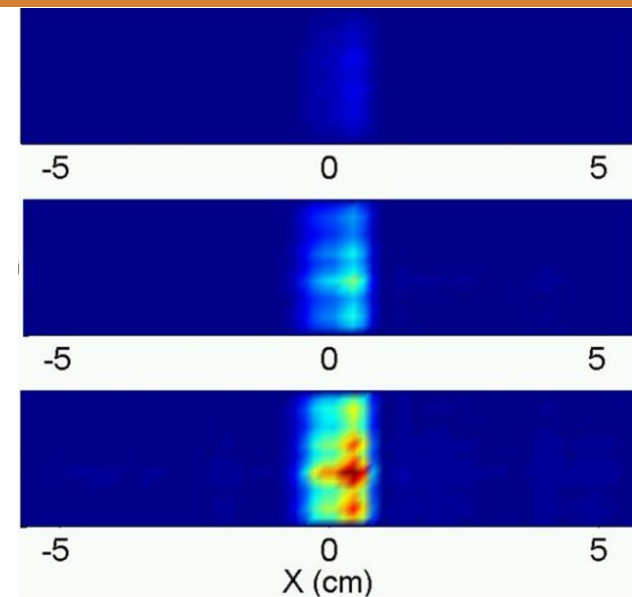


Traditional SHM



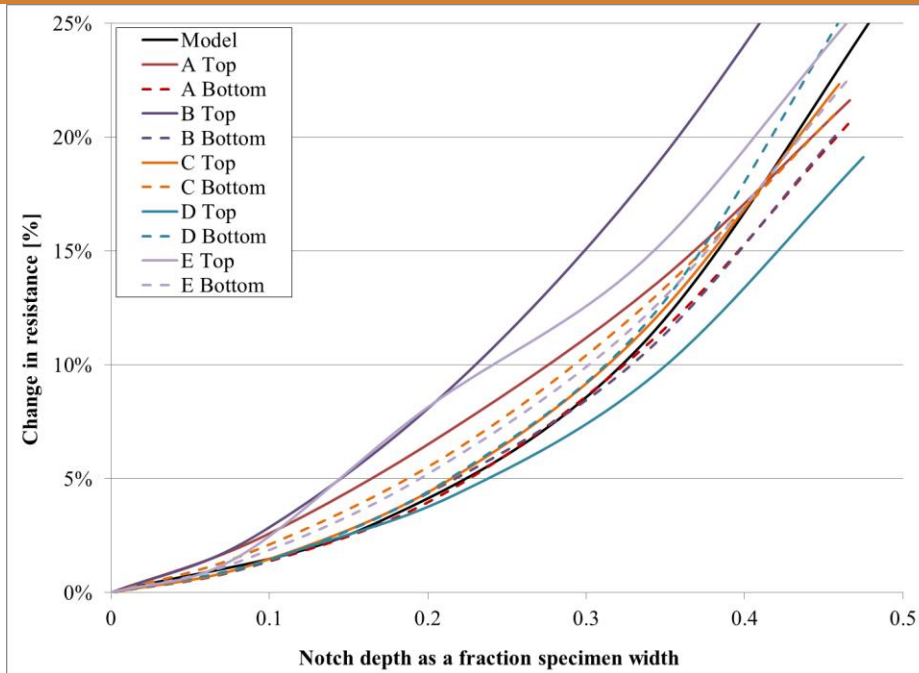
CNT-based SHM

# Fine Grid Impact Results (AF08-T023)



- **Damage shifts CNT links in affected zone, increases resistivity**
  - nearly linear increase in % resistance change with impact energy
  - < 1% change in resistance away from impact zone
- **Surface & sub-surface images produced in post-processing**
  - 20 joule impact caused ~10-20% resistance change (no visible change)
  - 40 joule impact caused ~20-30% resistance change (no visible change)
  - 60 joule impact caused ~40-60% resistance change (no visible change)

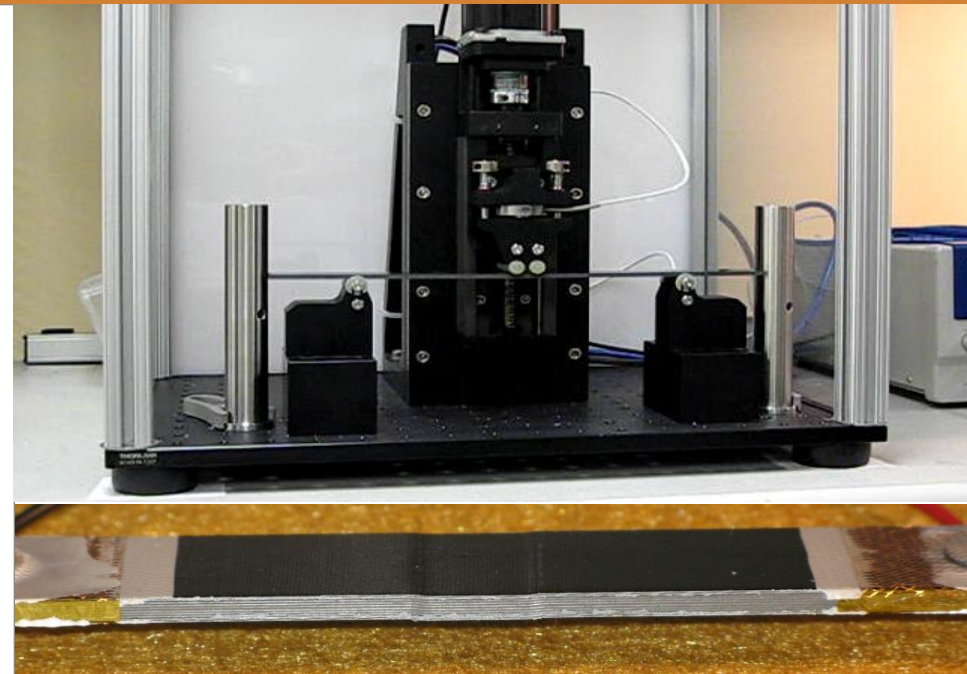
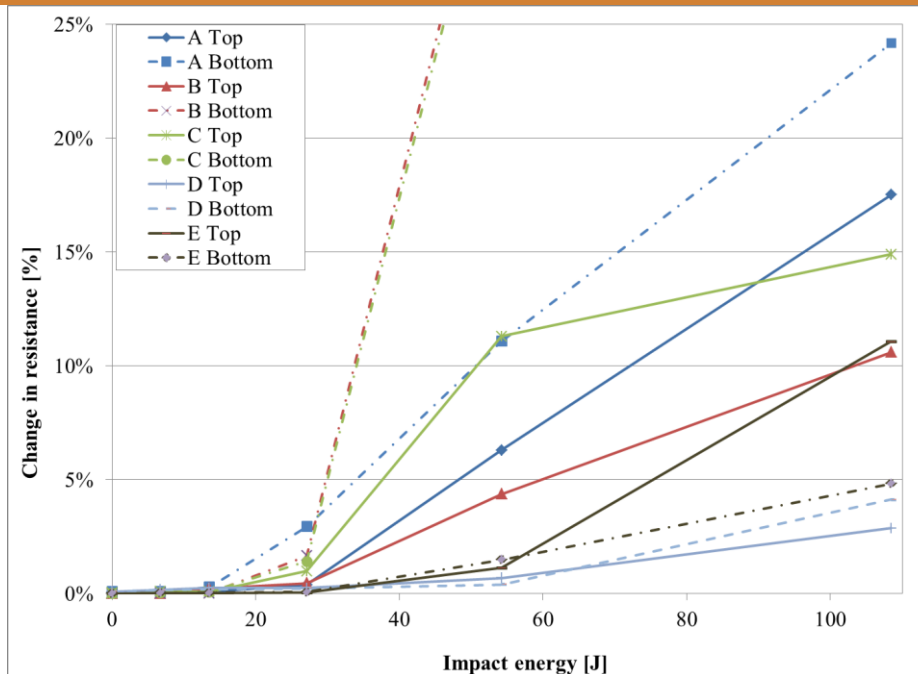
# Sparse Electrode Notch-Cutting Tests (N111-067)



- **Detection sensitivity strong function of CNT network aspect ratio**
  - 2400 mm<sup>2</sup> CNT w/160 mm<sup>2</sup> damage yields ~25% in resistance increase
  - same damage in 1 m long strip of same width would yield ~2% change
  - 10 mm<sup>2</sup> damage would still be over noise floor
- **Simple 2D network resistor model in good agreement with data**

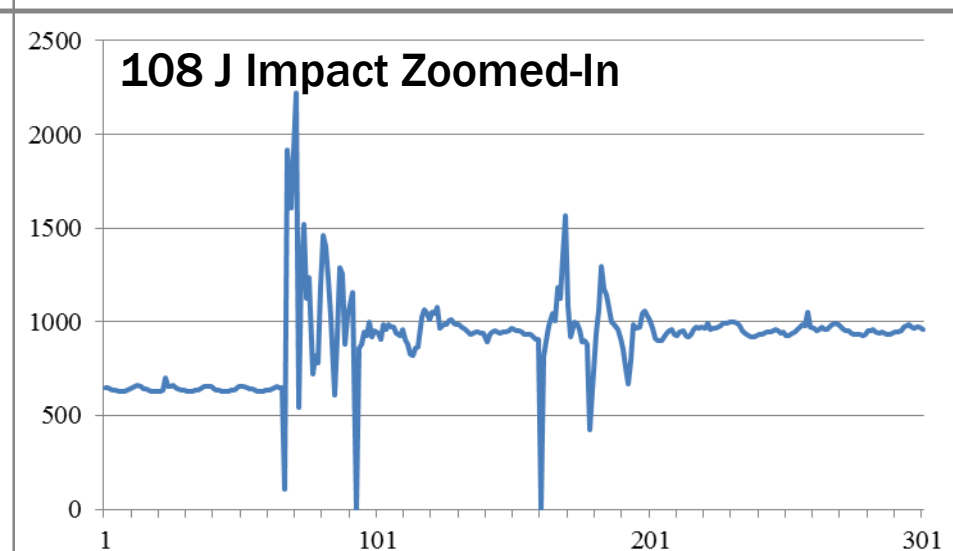
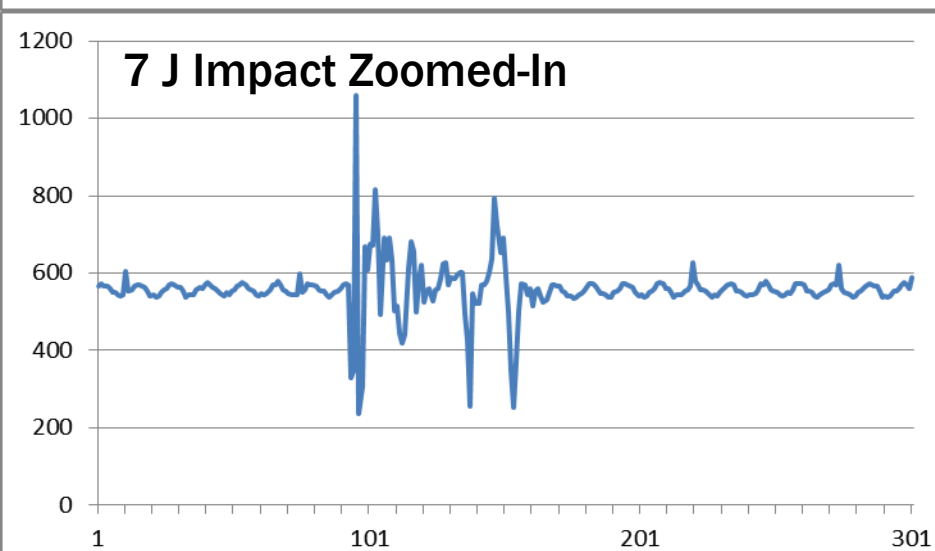
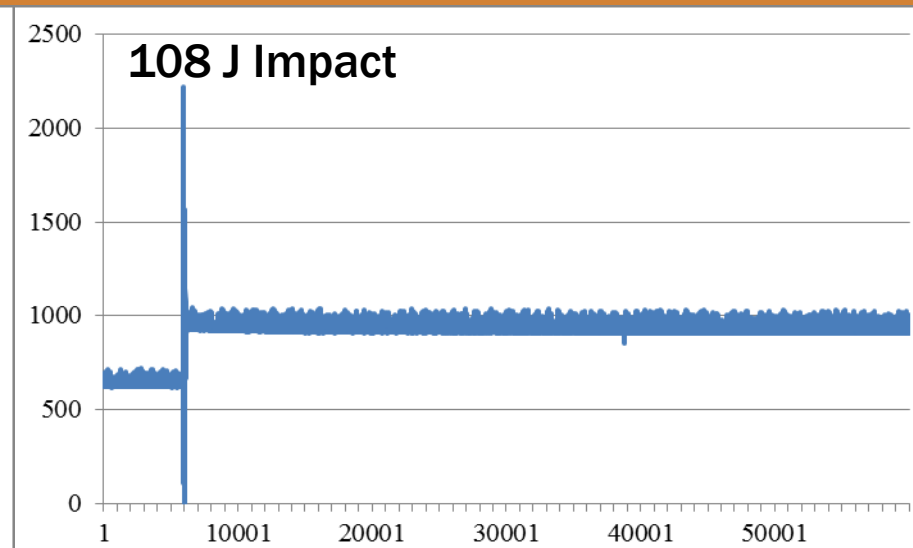
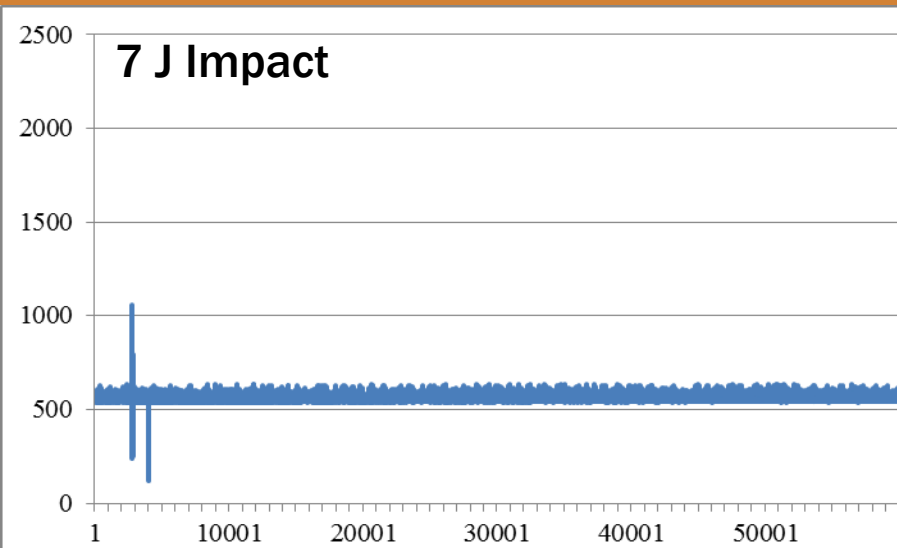


# Sparse Electrode Impact Results (N111-067)



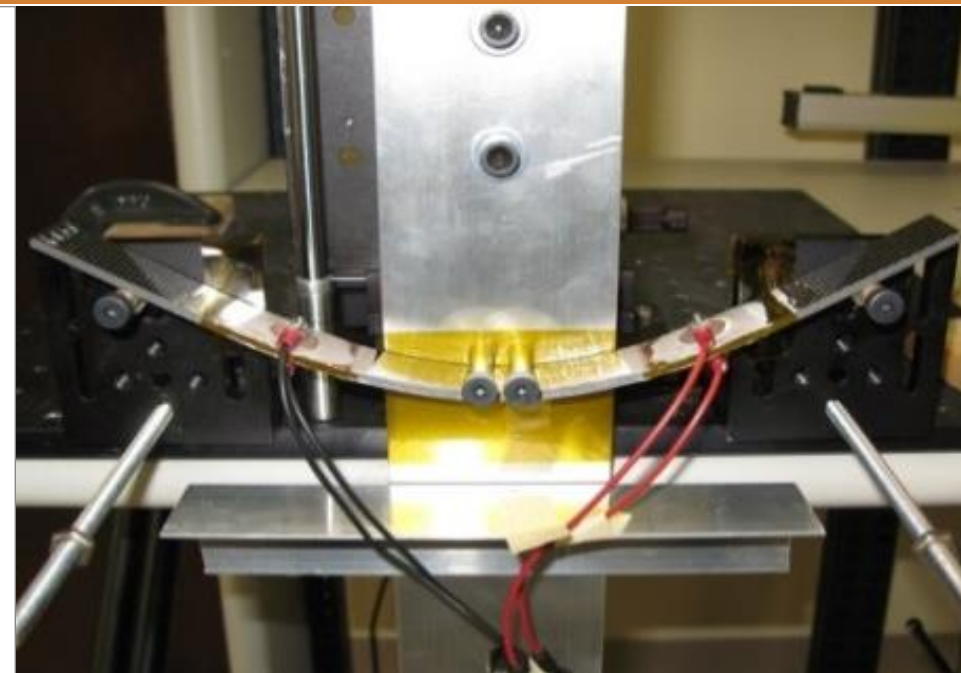
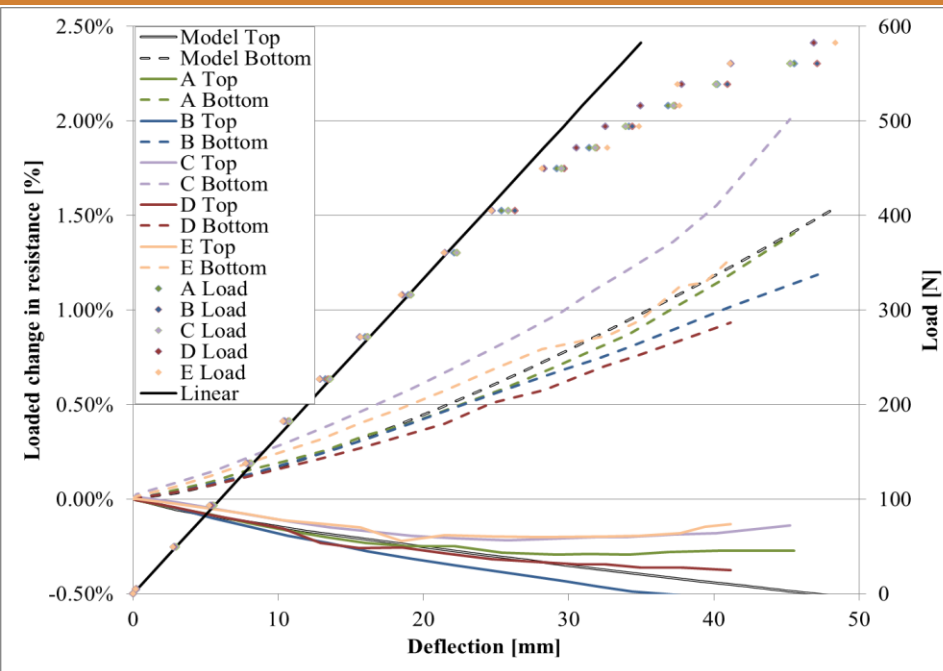
- **Impacts below threshold of 30 J had <0.25% change in resistance**
  - impacted surfaces exhibited >1% change in resistance after 30 J impacts
  - majority of specimens showed increase of ~15% after 110 J impacts
  - possible to increase CNT monitoring patch length to 1 m with 0.1% change
- **Variability due to impact events, could be observed in “dents” too**

# Impact Test Acoustic Response (N111-067)



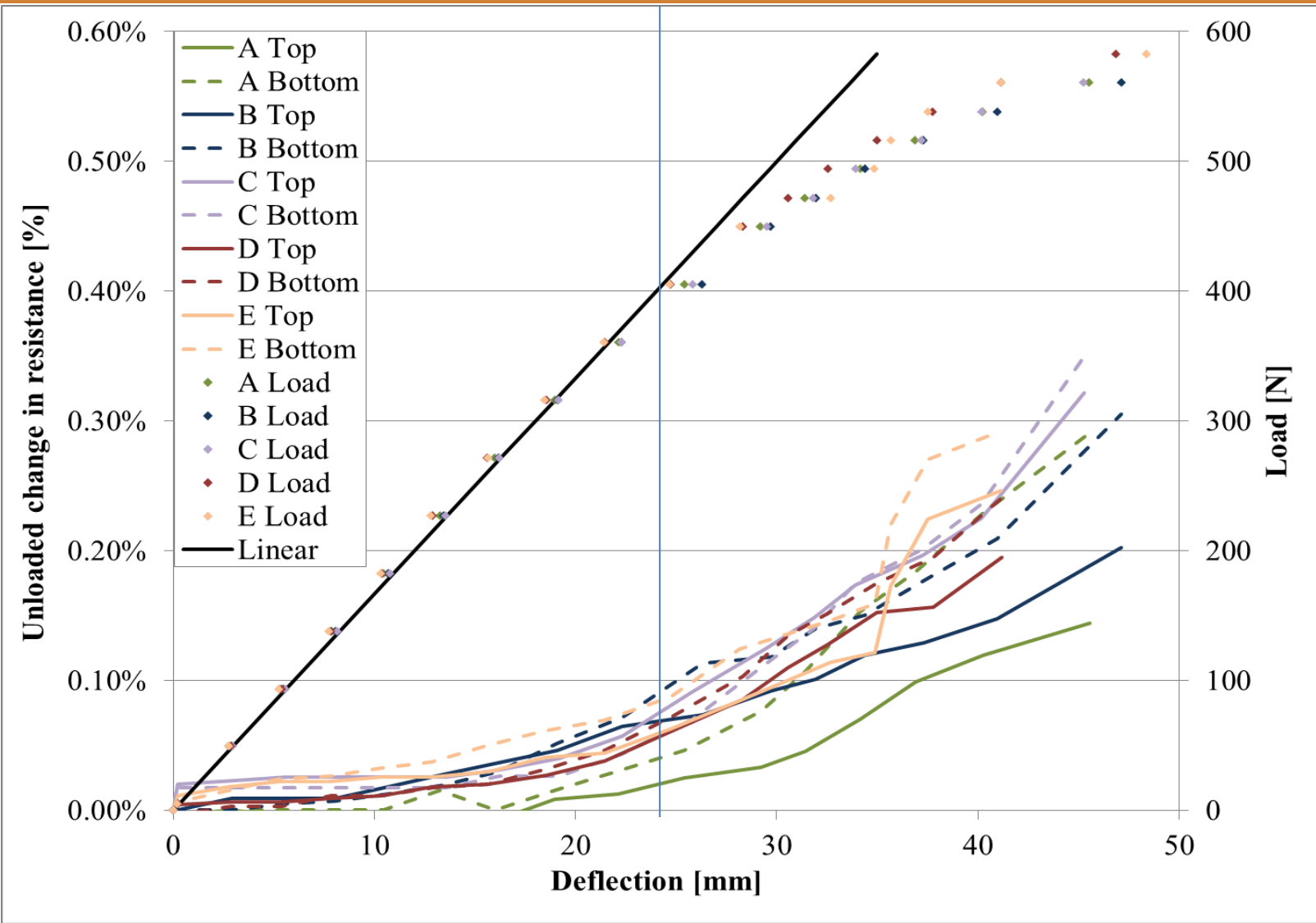


# Sparse Electrode 4-Point Bent Results Under Load

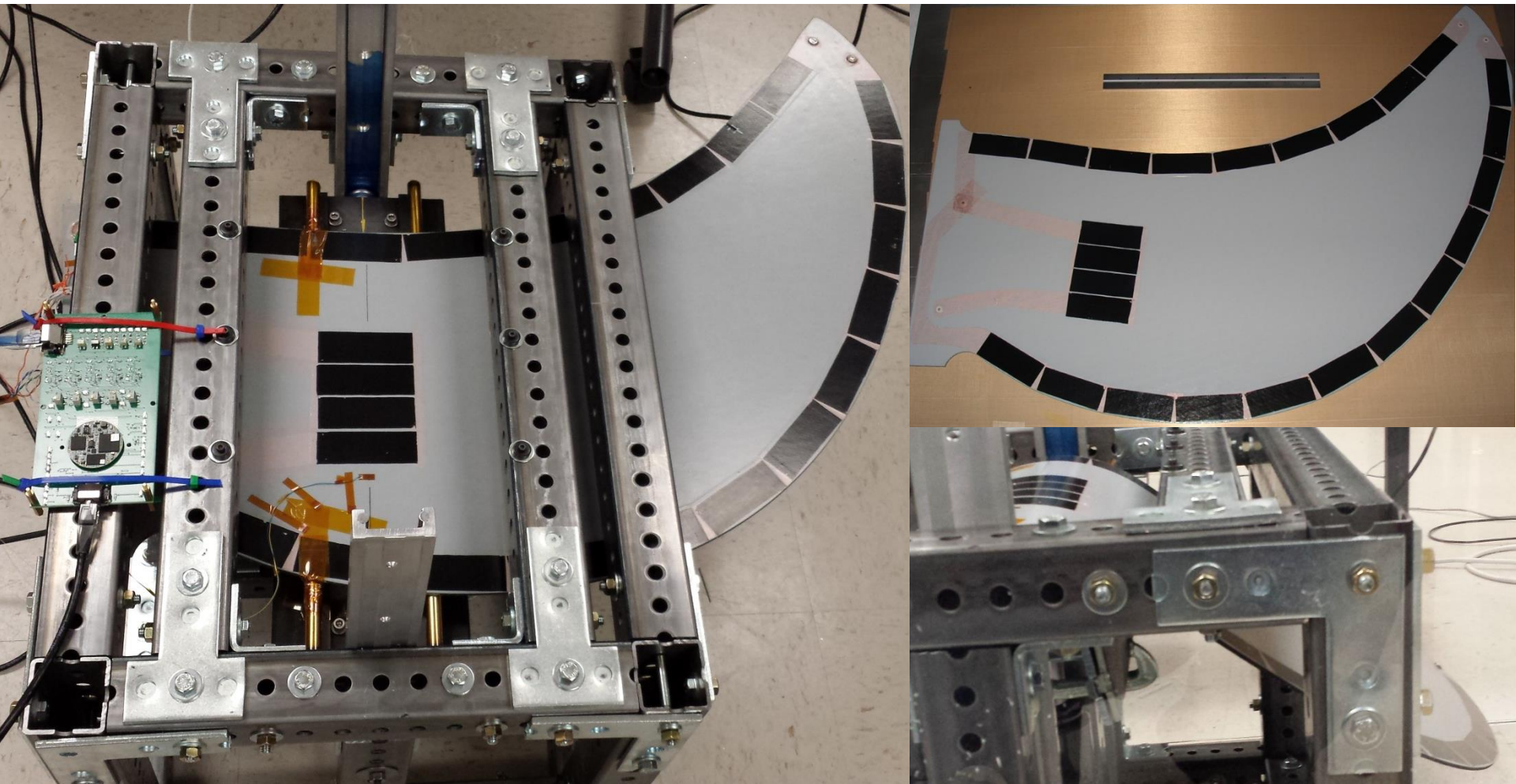


- **Resistance is proportional to strain for low displacement**
  - load/displacement curves for all specimens are in close agreement
  - tensile-side resistance increases due to CNT network being stretched-out
  - compressive-side resistance decreases due to CNT being pushed together
- **Permanent resistance increase after 25 mm deflection (>400 N)**

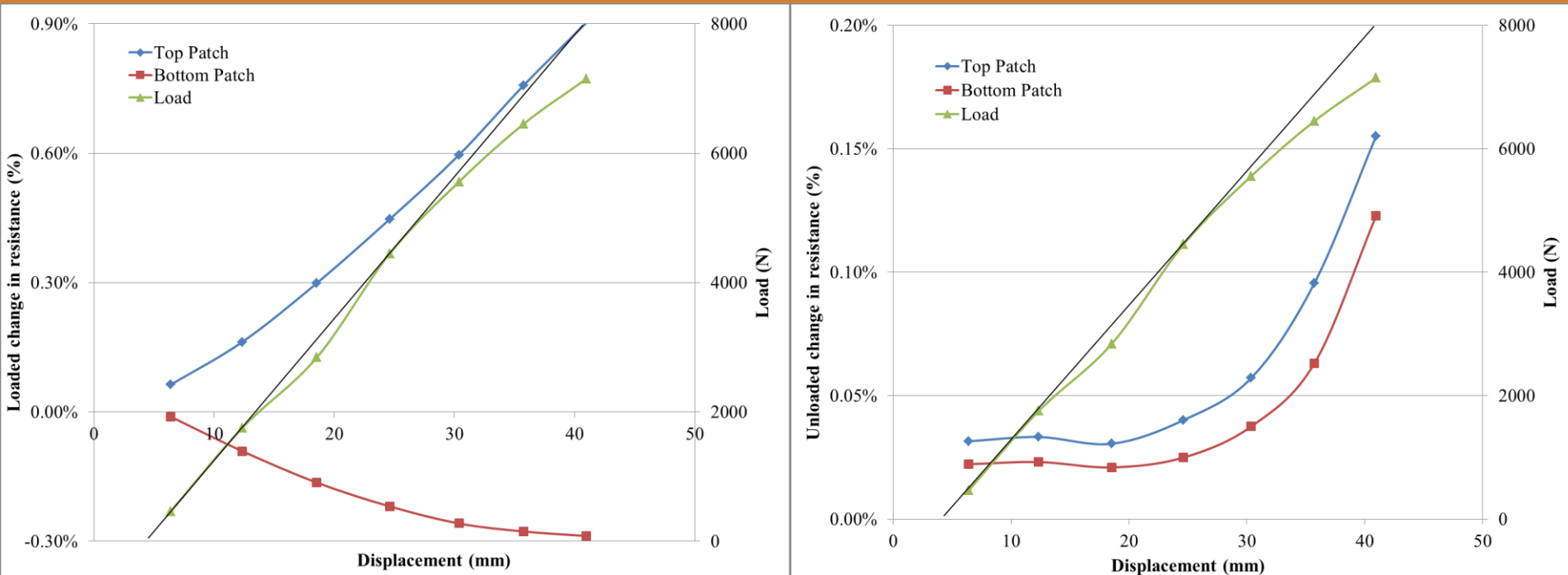
# Unloaded Bend Test Results (N111-067)



# 1m CFRP Submarine Propeller Test Specimen

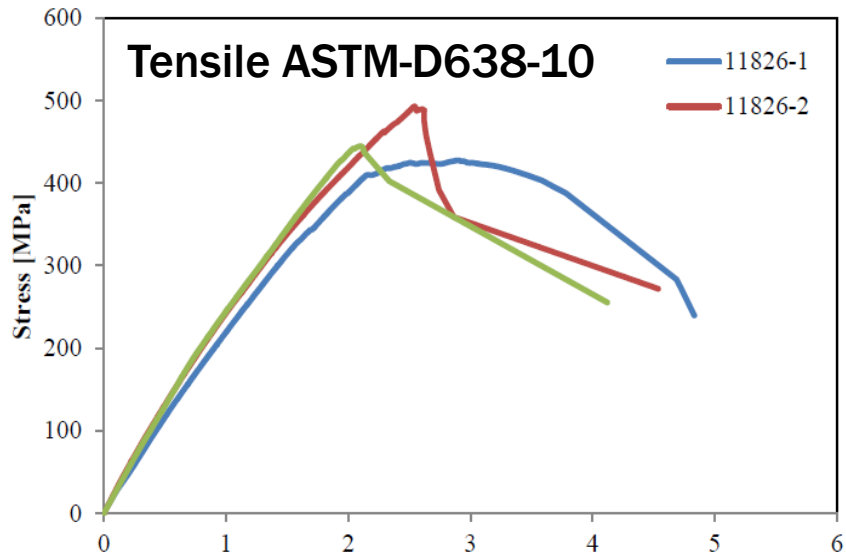


# 4-Point Bend Results: Loaded vs Unloaded Results

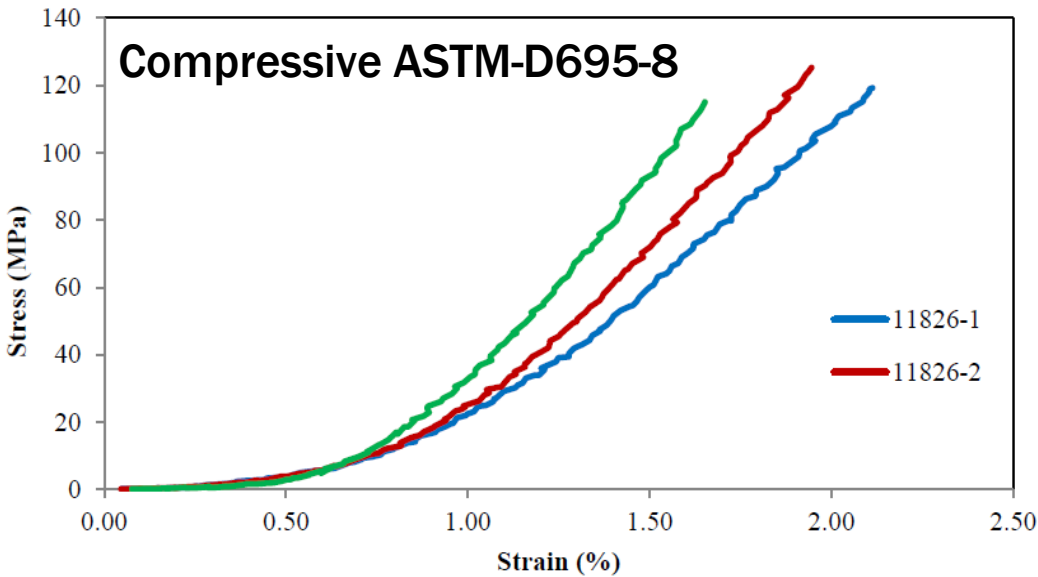


- **Same trends observed in 1 meter specimen as smaller coupons**
  - tensile-side resistance increases linearly with enforced displacement
  - compressive-side resistance decreases linearly with enforced displacement
- **Permanent resistance increase after 25 mm deflection (>4 kN)**

# Effect of CNT on Laminate Mechanical Properties



- 4 sets of ASTM tests performed professionally by testing house
- **CNT surface layer statistically has no effect on any mechanical stiffness or strength properties in normal operating strain ranges**



Impact ASTM-D256-10	
Izod Specimens	Average Strength
Baseline	33 ft-lbs/in
CNT on surface	37 ft-lbs/in



# Technical & Business Contact

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